# Rock Strength Measurements on Mars (Using the MSL Drill as a Scientific Instrument)

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**May 2, 2017**

# DARSI Overview

- Drill Analysis Rock Strength Investigation (DARSI)
  - Uses the drill on the Mars Science Laboratory (MSL) as a scientific instrument to provide an indication of the compressive strengths of the rock we drill on Mars
  - We take performance data from the drill on Mars and use that to determine the energy needed to drill rocks there
  - We manufactured rocks in the lab with known properties
  - We used a testbed drill just like the one used on MSL to drill into the manufactured rocks
  - We compare the performance we see in the testbed to that of what we are seeing on Mars

# Gale Crater Study Area

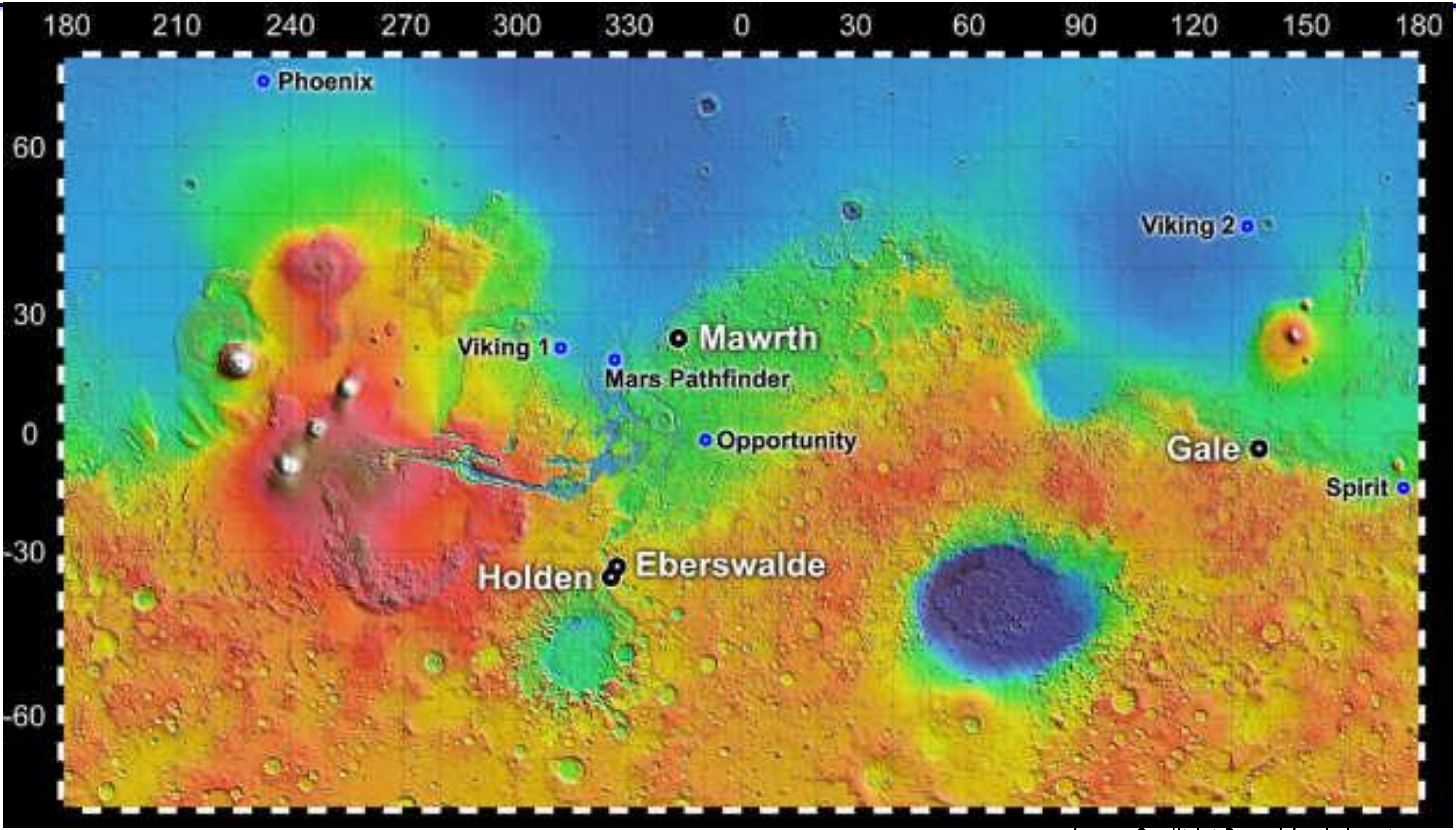



*Image Credit Jet Propulsion Laboratory*

- Gale Crater is located on the Martian dichotomy

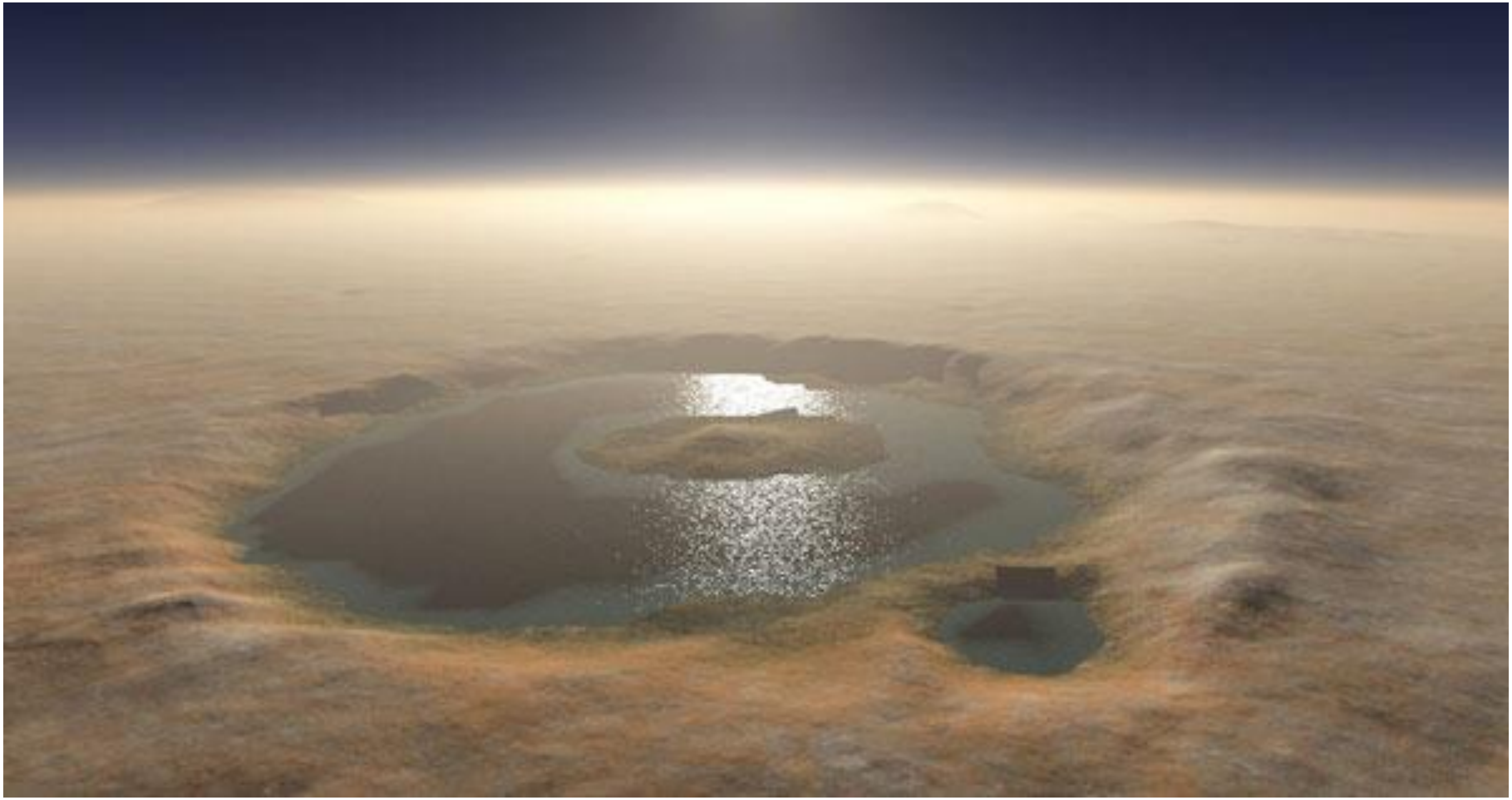
# Gale Crater Size



# The Prospect of Gale's Wetter and Warmer Past



*Image Credit Jet Propulsion Laboratory*



Orbital data suggested that Gale Crater may had been home to a large lake and was a major factor in the decision to select Gale crater as the area of study for MSL

# Gale Crater Sedimentary Setting

*Image Credit Jet Propulsion Laboratory*

# The Robotic Scientist Goes to Work

- The MSL Rover is bristling with scientific instruments

*Image Credit Jet Propulsion Laboratory*

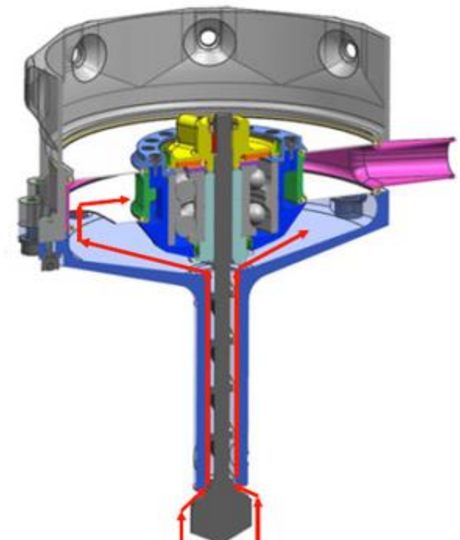
# Scientific Measurements

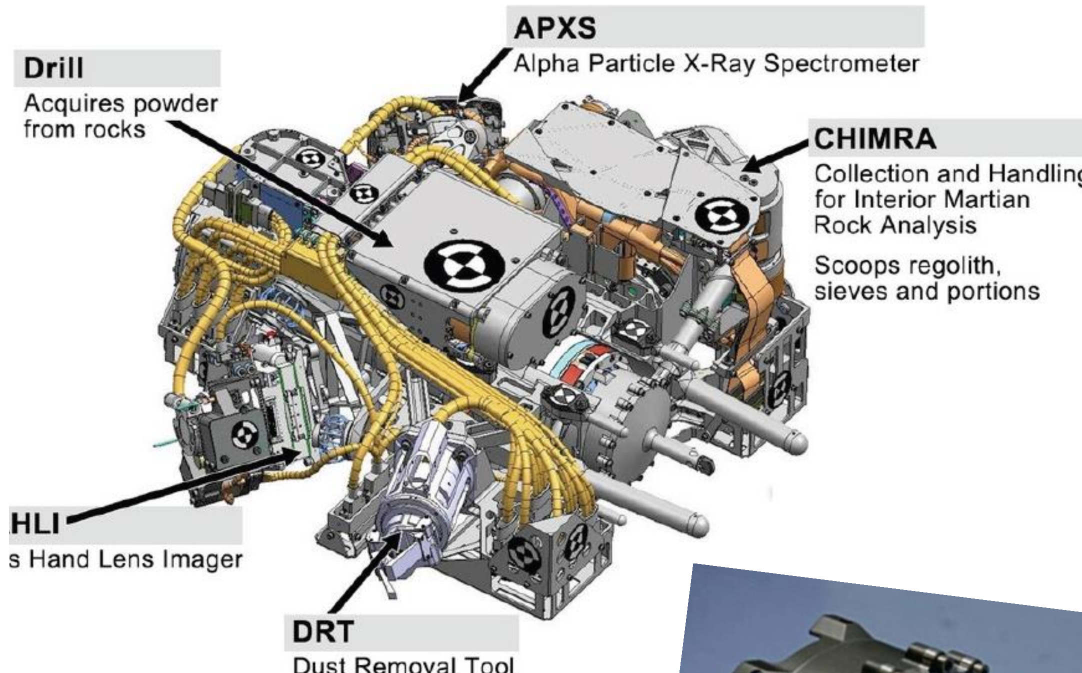
- APXS (Alpha-Particle X-ray Spectrometer)
  - Elemental chemistry
- ChemCam Laser Induced Breakdown Spectroscopy (LIBS)
  - Chemical compounds
- MAHLI (Mars Hand Lens Imager)
  - Microscopic images
- SAM (Sample A… Mass Spectrometer, GC Column and Tunable L… …eter

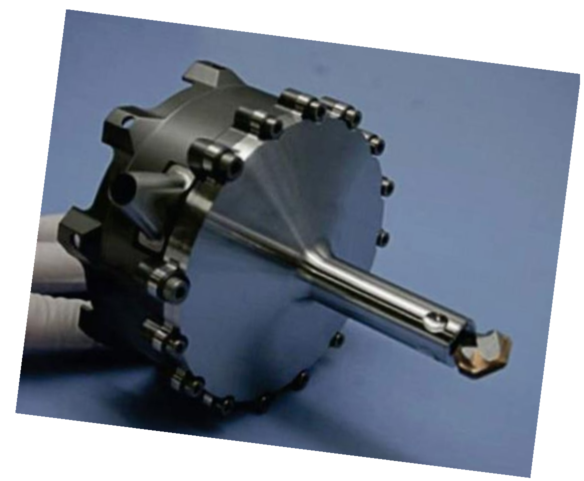
  Requires Processed Grains <1mm
  - Evolved molecular chemistry
- CheMin, short f… Mineralogy," is an XRD/XRF instrument

  Requires Processed Grains <150μ
  - …ology

# The Powder Acquisition Drill System (PADS)



- Creates powdered fines as it drills
- Fines are augured up the drill stem then delivered to CHIMRA for sieving and portioning and eventual delivery to SAM and CHeMin

*Images Credit Jet Propulsion Laboratory*

# MSL Drill Operations



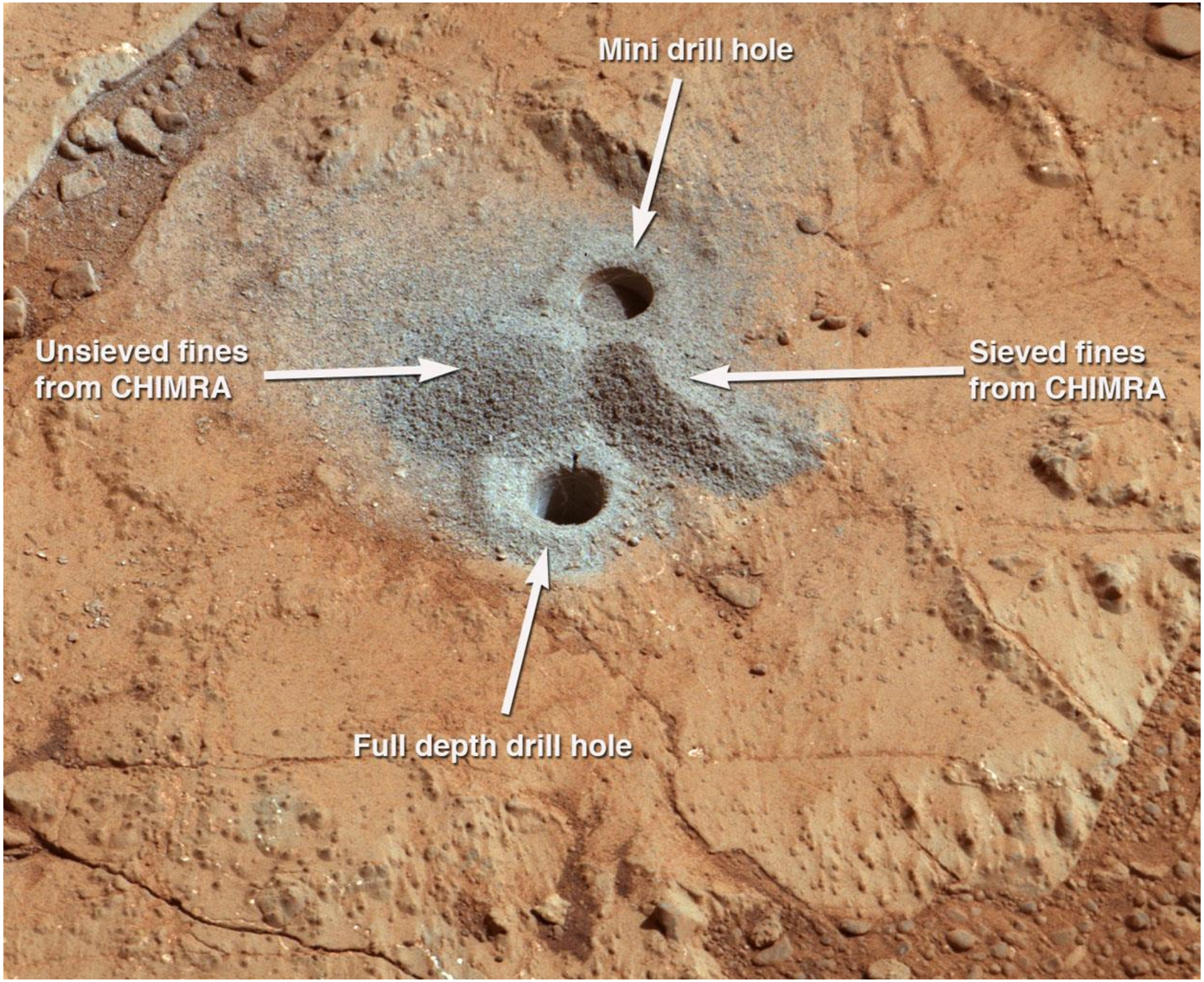
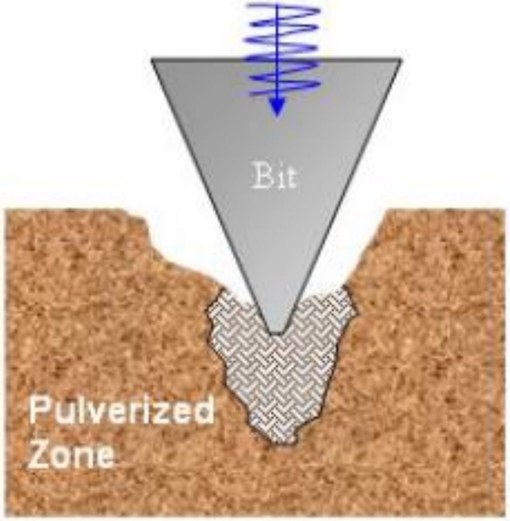



*Image Credit Jet Propulsion Laboratory*

# Rotary Percussive Drilling

- PADS is a rotary percussive drill
- Chisel shaped bit as opposed to a cutting bit
- Highly concentrated forces fracture rock in a pulverized zone extending several times greater than the depth of penetration [1]
- Rotation facilitates cuttings removal and transport but contributes little to rock fracture in this type of system



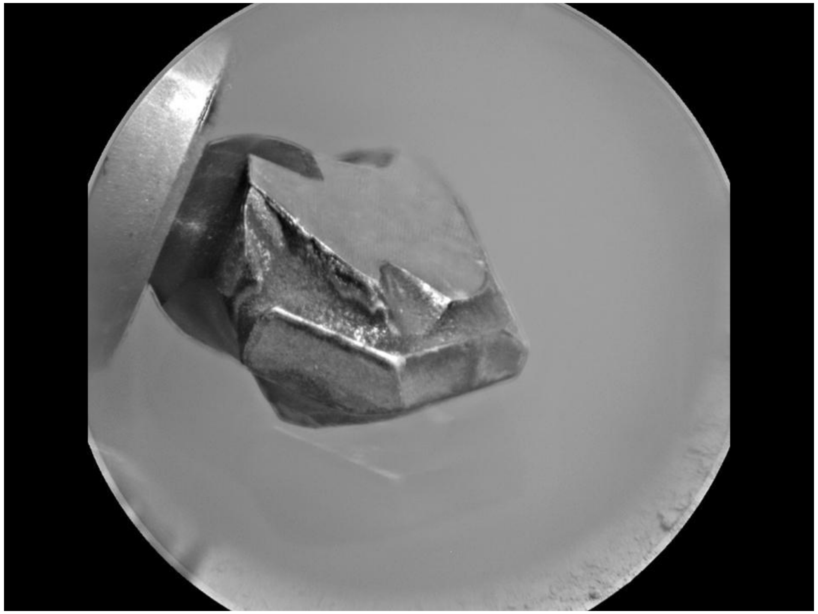



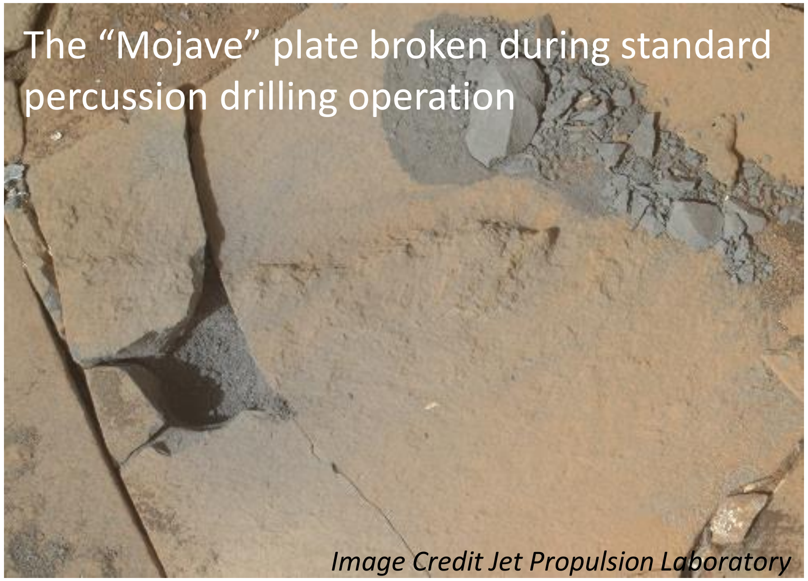
*Image Credit Jet Propulsion Laboratory*

- Percussion is facilitated by use of a voice coil mechanism
- There are six discreet voice coil levels (only four used in flight)
- Voice coil percussion allows changing percussion energy while spindle speeds remains constant

[1] Gang Han, Mike Bruno, 2005, Dynamically Modelling Rock Failure in Percussion Drilling, ARMA/USRMS 05-819

# Standard vs Reduced Percussion

- Flight software adjusts the voice coil level (VCL) level to maintain the required rate of penetration (ROP) and weight on bit WOB
  - Standard drilling configuration is an operational algorithm designed to minimize the total drilling duration by biasing toward the highest VCL
  - Reduced percussion is a more adaptable algorithm that guides toward the lowest VCL possible while still maintaining reasonably fast progress into a rock

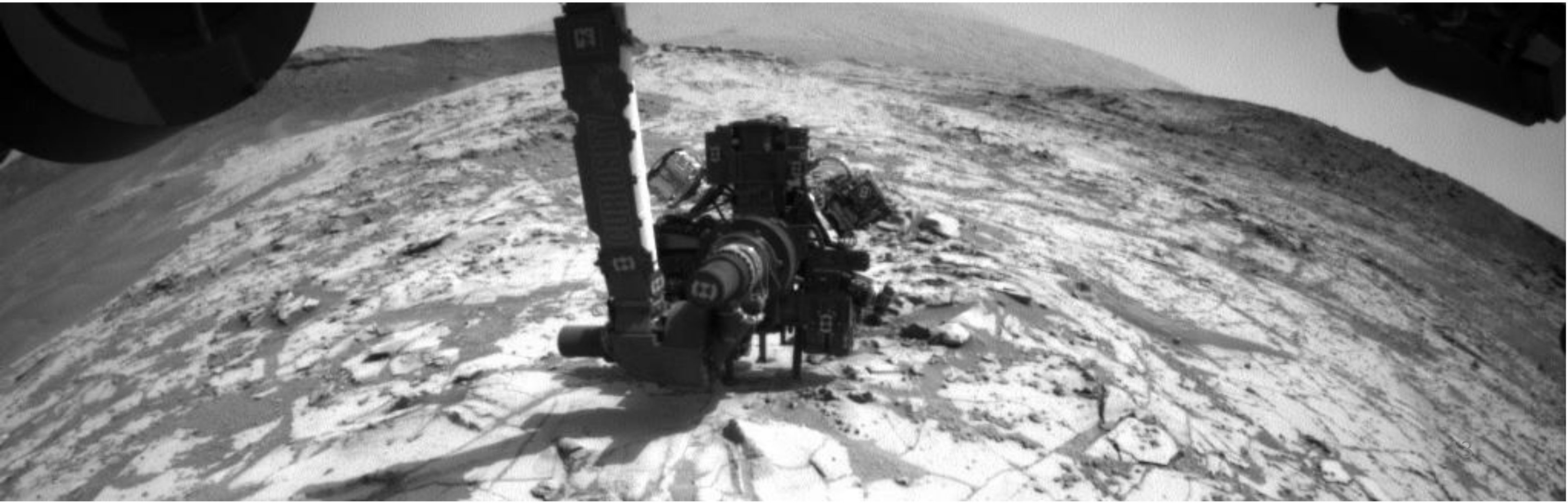



| Parameter | Standard | Reduced |
|---|---|---|
| Initial percuss level | 4 | 1 |
| Step-up min ROP (mm/sec) | 0.16 | 0.05 |
| Step-down max ROP (mm/sec) | disabled | 0.13 |
| Step-down min WOB (N) | 50 | 50 |
| Fault min ROP | 0.025 | 0.025 |

# Performance Parameters

- In order to provide autonomous operation and monitor the health of the system PADS has sensors that measure:
  - Current delivered to the actuators
  - Temperatures of the actuators
  - Positions
  - Force measurements, including the preload on the stabilizers and the weight on the bit (WOB)
  - Rate of penetration (ROP)
  - Voice Coil Level (VCL)

*Image Credit Jet Propulsion Laboratory*



# PADS as a Scientific Instrument

- The drill was not designed as a scientific instrument
- Hypotheses was that we can use the performance data from the drill to tell us something about the mechanical properties of the rocks
- Energy per unit-volume-comminuted is an empirical geotechnical measurement
- The energy needed to process rock into smaller pieces does indeed map to the compressive strength of rocks [1]
- For PADS, percussion energy is the main component in rock comminution
  - We know the percussive energy delivered at each VCL and we know the percussion rate

| VCL | Energy (J) | Rate (Hz) |
|---|---|---|
| **1** | 0.05 | 30.1 |
| **2** | 0.20 | 30.1 |
| **3** | 0.31 | 30.1 |
| **4** | 0.45 | 30.1 |

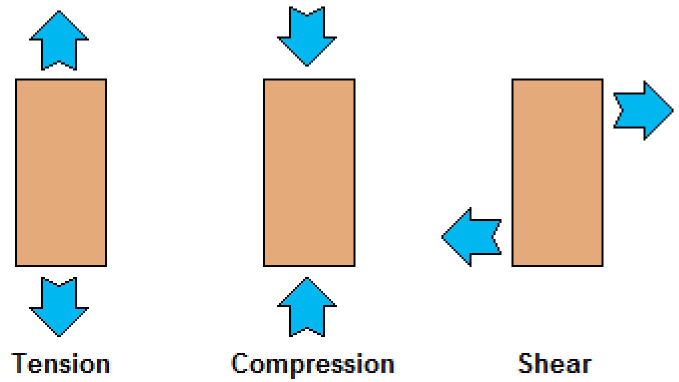
  - We know the depth over time (ROP)
  - We know the VCL profile



[1] Thomson, B. J.2013, Estimating rock compressive strength from Rock Abrasion Tool (RAT) grinds

# Rock Strength

- Rock strength refers to a resistance to specific stress modes
- Uniaxial Compressive Strength (UCS) of a rock can be described as its resistance to compressional force in one direction without lateral restraint
  - Stress vectors are confined to one direction by loading a cylindrical or cubed sample
- Other feasibly applied, and measurable stresses include tensile and shear modes



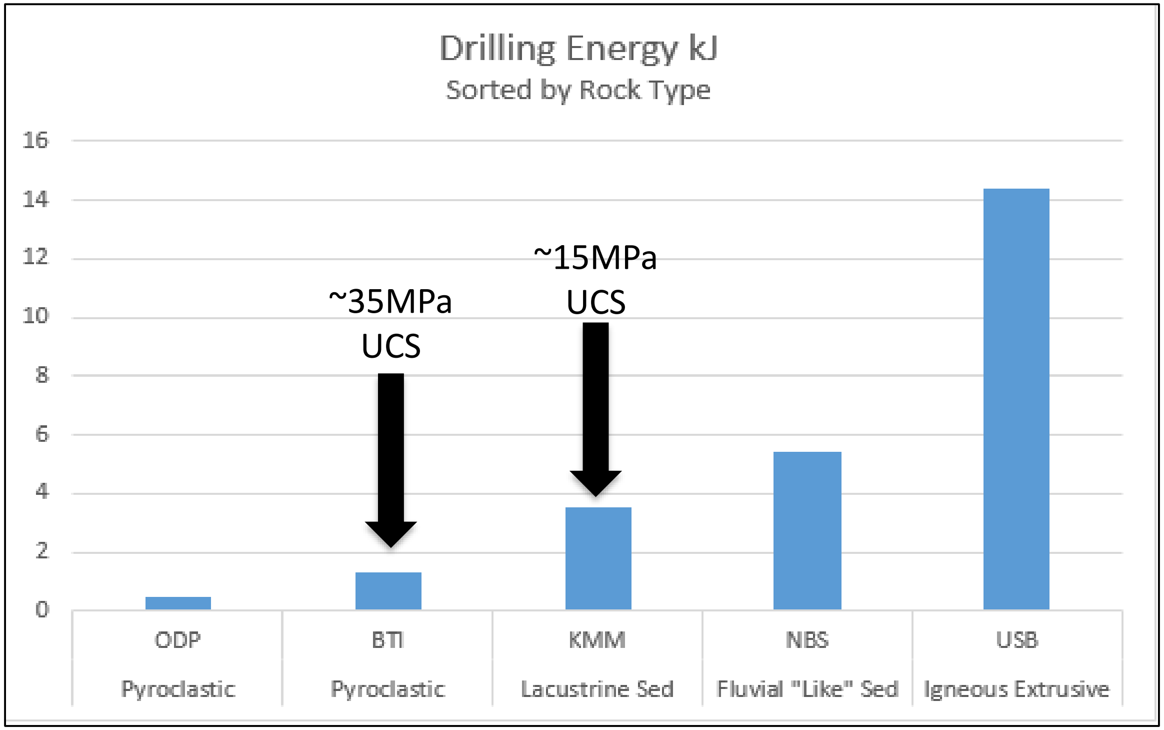
# Compressive Strength and Percussion Energy

- Think of sedimentary rocks as a structural building
  - The strengths of the posts and beams and the manner in which they are assembled contribute the strength of the structure
- Strength and resistance to drilling are similarly affected by the structural elements and their modes of construction
- We can correlate rock strength to its ability to resist drilling
  - **This is only true where the structural assemblages remain in-family**
    - Case in point: In drill testbeds at JPL we have observed that a rhyolitic tuff requires less percussive energy to drill than a consolidated mudstone of much lower compressive strength

# Rock Structure and Drilling



Mars 2020 BBC (rotary percussive)
Coring drill
40 N Weight on Bit
Coring bits only

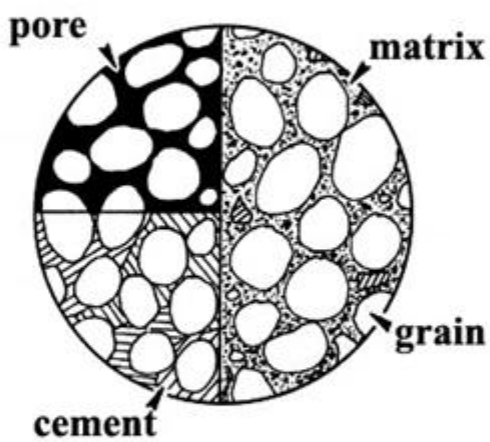


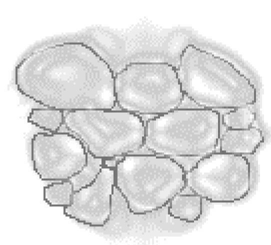

**We see a correlation in drill energy when rocks are binned by structure first, then by strength**

# Structural elements affecting the strength of sedimentary rock

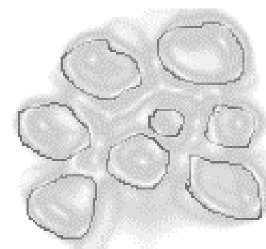


- Grain mineralogy, shape, and size distributions affect compressive strength
- Secondary mineralization processes (lithification) strengthens rock
- Mechanical and chemical weathering processes tend to weaken rock

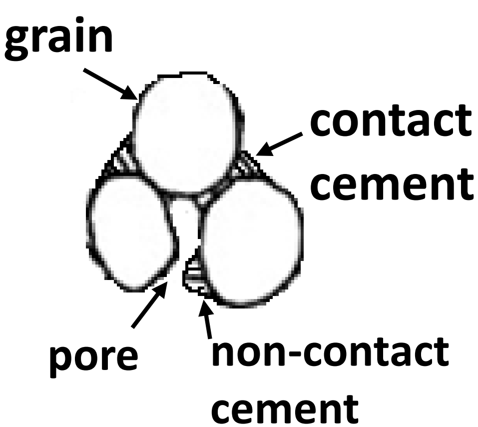


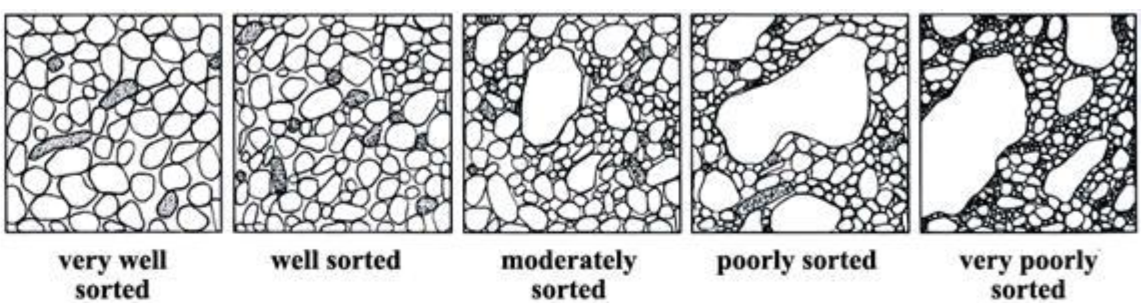



grain supported



matrix supported

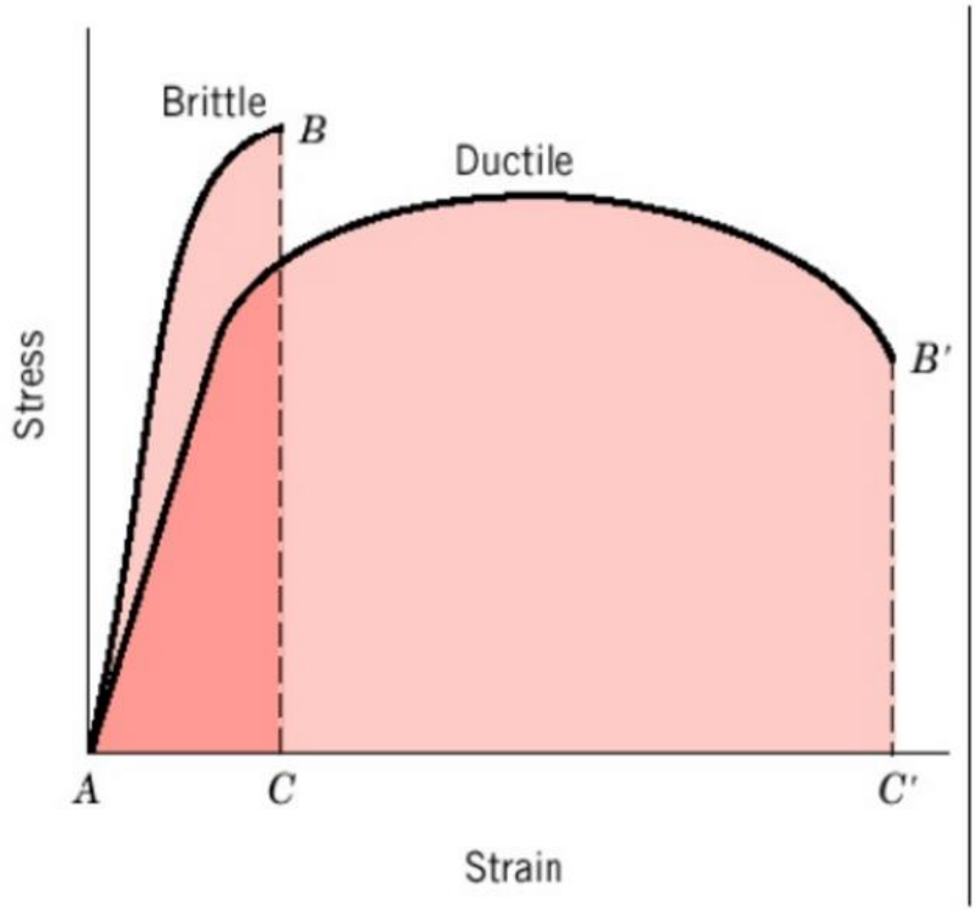



*Images Public Domain*

# Mechanical Properties

- Rocks are semi-brittle
- This means that many rocks exhibit some ductile behavior
- Where the structural elements of rocks add ductility, more percussion energy is needed to initiate fracture
  - For a given strength, ductile rocks are "tougher"






*(Figure) Gang Han, Mike Bruno, 2005, Dynamically Modelling Rock Failure in Percussion Drilling, ARMA/USRMS 05-819*

# Strength Toughness

Strength measures the resistance to failure, given by an applied stress

Toughness measures the energy required to initiate and/or propagate fracture

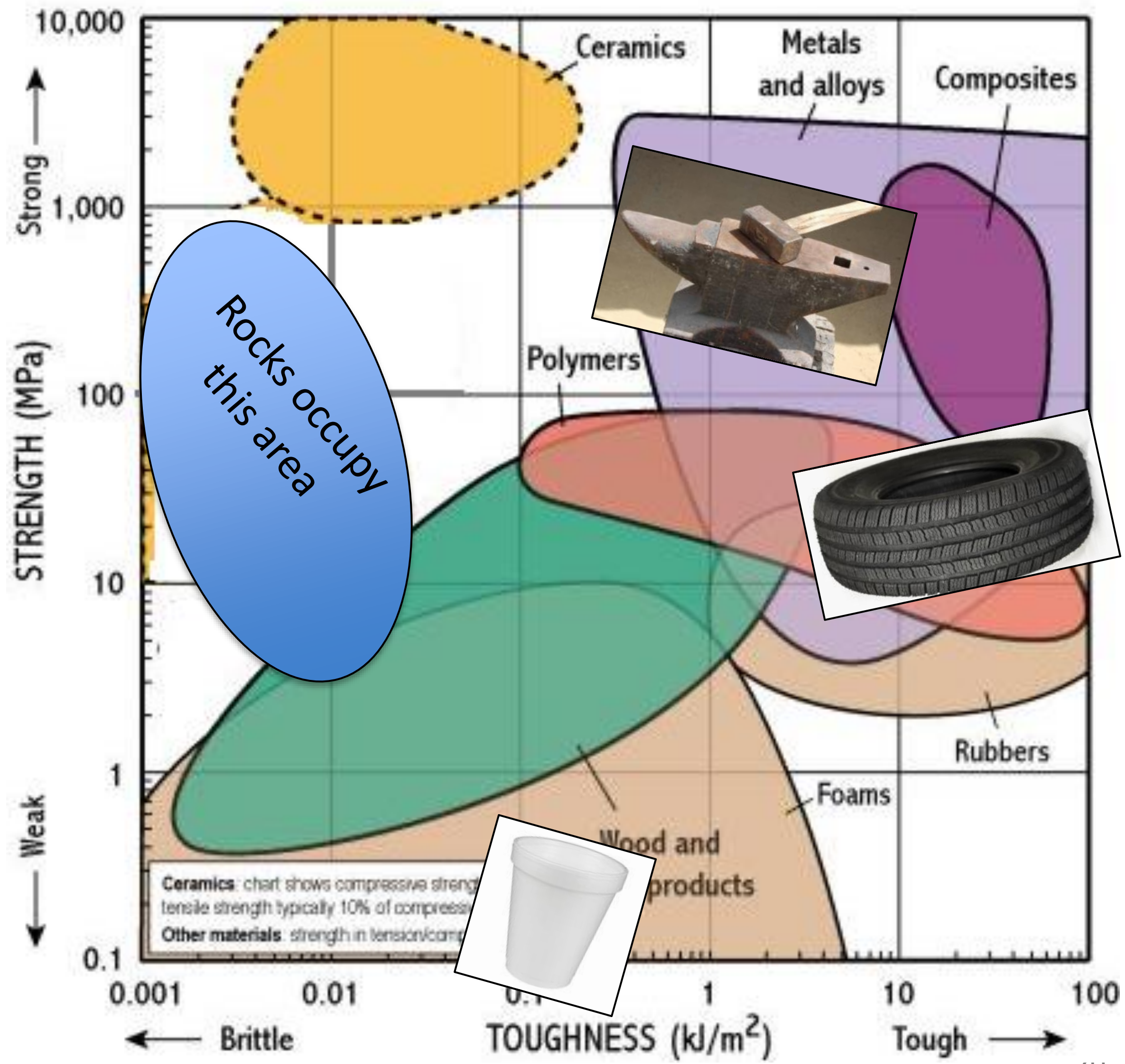
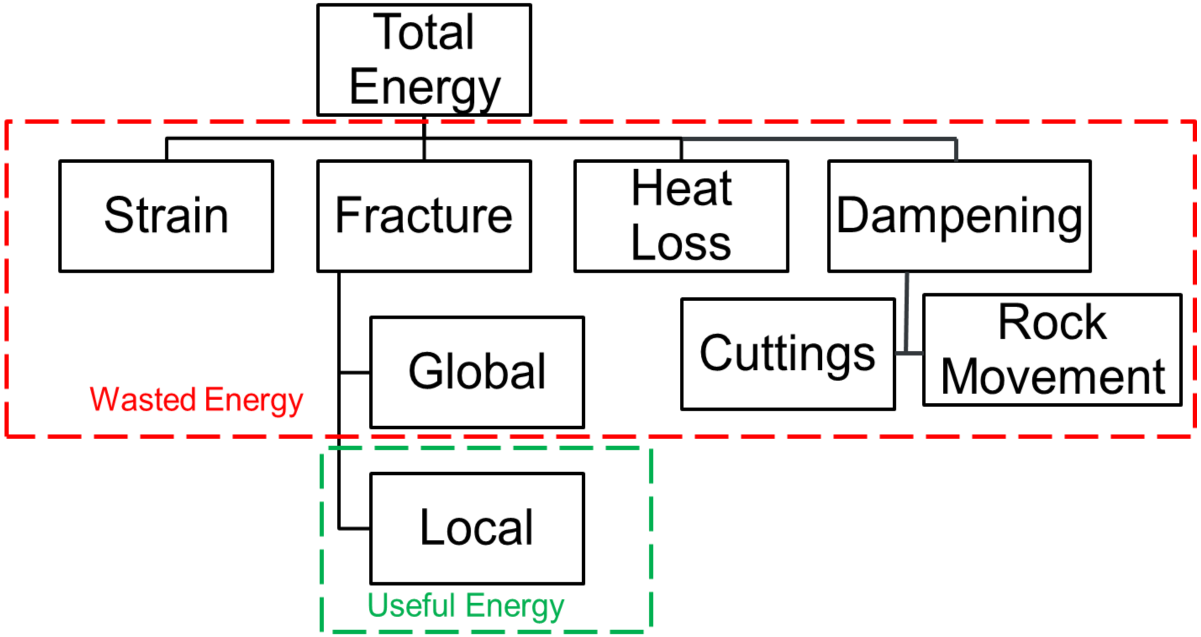



*Figure: materials.eng.cam.ac.uk*

# Energy Budget

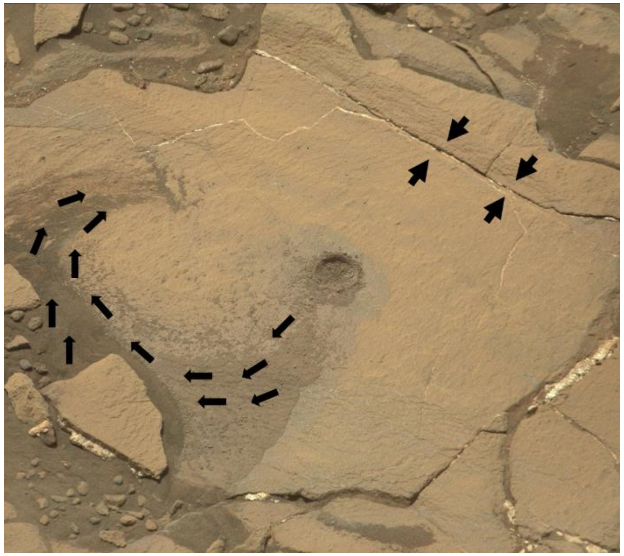
- Not all of the percussion energy goes into comminution
- Much of the energy in rock-drilling processes contribute to elements other than the creation of the borehole
- Rock strain, heating, dampening and global fracturing are elements that contribute to the total energy budget.
- Only the energy going into **local fracture** is considered **useful energy** in percussive drilling



# Energy Loss Mechanisms

- Strain
  - Expressed as an alteration of the volumetric shape of the rock under stress without (or prior to) fracture
- Heat
  - Friction generated at the rock to bit interface
  - The process of straining the rock
  - Generated in the mechanisms
- Dampening
  - Cuttings
    - Reduction in local percussive impulse energy contributing to local fracture in the rock
  - Rock Stability
    - Rock movement during the drilling operation can also dampen the effectiveness of percussion
- Fracture
  - Global Fracture
    - Where stress is carried into the rock causing rock fracture
  - Local Fracture
    - This is the useful comminution under the bit
    - This is what creates the borehole

*Images Credit Jet Propulsion Laboratory*



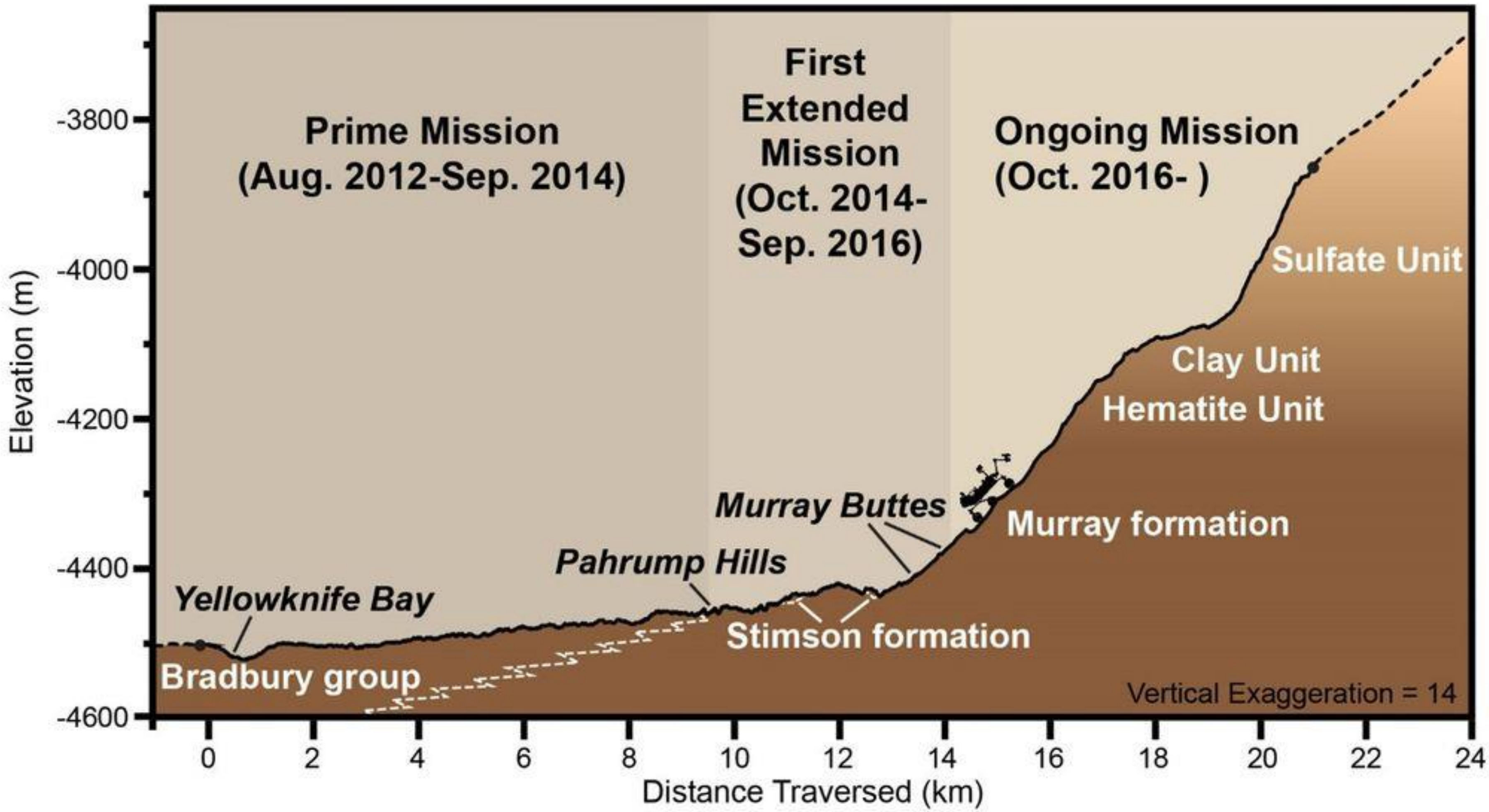
*First attempt at a full drill at Marimba on Sol 1420*

*Drill attempt on Sol 867, at the Mojave drill site (last standard percussion drill site)*

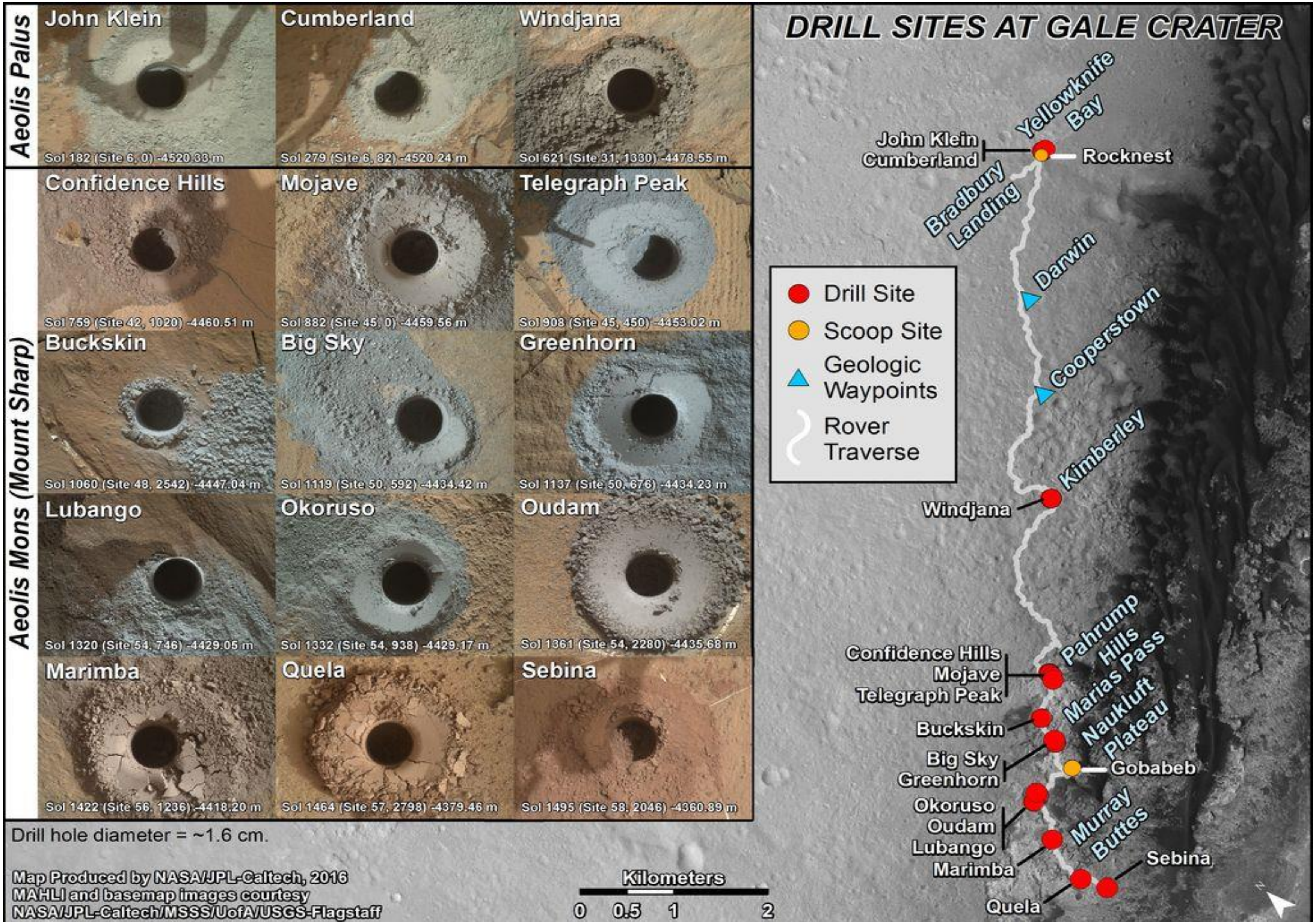
# Murray Stimson Units



*Image Credit Jet Propulsion Laboratory*



# Outcrops Drilled During the Mission



# Process for indicating the rock strengths of the Murray and Stimson

- Determine the Relative Rock Strengths
  - Determine the VCL profile
  - Rocks that require higher voice coil levels are stronger than rocks requiring lower voice coil levels
  - Calculate the percussion energy needed to drill
    - Higher percussion energies within the highest voice coil level equates to higher rock strength
    - Normalize the data by calculating the energy needed to bore out a unit volume of rock (J/cc)
- Quantify Strength Range
  - Provide rocks of like structure and known strengths
    - We make these in the EMSiL
  - Drill into them with a system that is the same as the drill on MSL
  - Calculate the percussion energy needed to drill at each VCL in the testbed
  - Normalize the data by calculating the energy needed to comminute a unit volume of rock (J/cc)
  - Compare the energies needed to drill rocks of known strength in the testbed to the energies needed to drill the rocks on Mars

# Example (Buckskin)

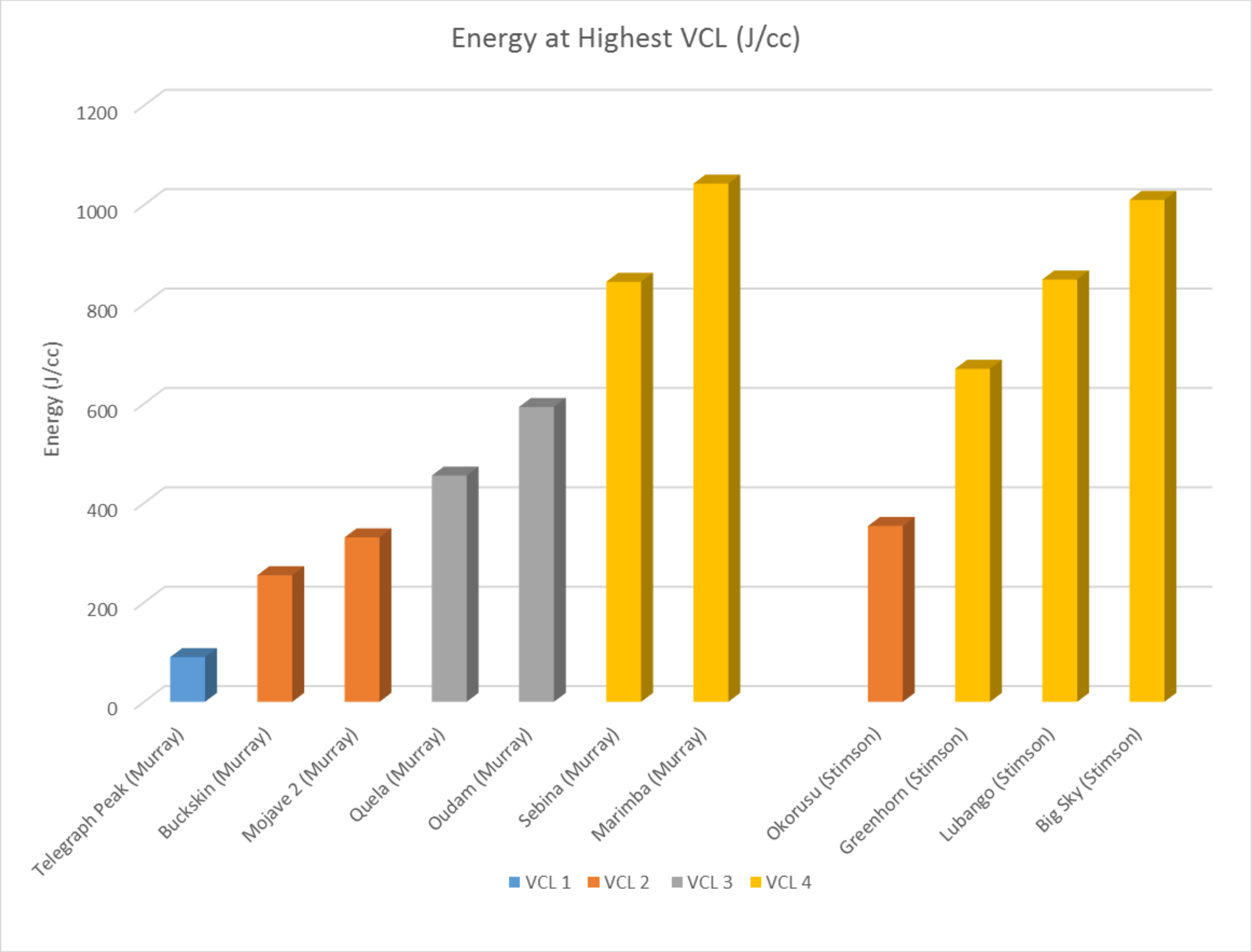
| | Buckskin | | | |
|---|---|---|---|---|
| Time (sec) | VCL | Depth (mm) | ROP (mm/sec) | Depth (mm) |
| 0 | 1 | 10.184 | 0.12 | 2.798 |
| 10 | | 10.914 | 0.096 | |
| 20 | | 11.402 | 0.081 | |
| 30 | | 11.893 | 0.073 | |
| 0 | 2 | 12.982 | 0.08 | 13.867 |
| 10 | | 14.134 | 0.086 | |
| 20 | | 15.261 | 0.09 | |
| 30 | | 16.517 | 0.094 | |
| 40 | | 17.744 | 0.097 | |
| 50 | | 18.815 | 0.098 | |
| 60 | | 19.868 | 0.099 | |
| 70 | | 20.885 | 0.099 | |
| 80 | | 21.866 | 0.099 | |
| 90 | | 22.905 | 0.099 | |
| 100 | | 24.188 | 0.101 | |
| 110 | | 25.809 | 0.105 | |
| 0 | 1 | 26.849 | 0.105 | 9.583 |
| 10 | | 27.506 | 0.103 | |
| 20 | | 28.099 | 0.101 | |
| 30 | | 28.752 | 0.099 | |
| 40 | | 29.342 | 0.097 | |
| 50 | | 29.939 | 0.095 | |
| 60 | | 30.545 | 0.094 | |
| 70 | | 31.082 | 0.092 | |
| 80 | | 31.664 | 0.091 | |
| 90 | | 32.248 | 0.089 | |
| 100 | | 32.798 | 0.088 | |
| 110 | | 33.408 | 0.087 | |
| 120 | | 33.927 | 0.086 | |
| 130 | | 34.41 | 0.085 | |
| 140 | | 34.886 | 0.084 | |
| 150 | | 35.333 | 0.082 | |
| 0 | 2 | 36.432 | 0.083 | 6.407 |
| 10 | | 37.441 | 0.084 | |
| 20 | | 38.427 | 0.084 | |
| 30 | | 39.488 | 0.085 | |
| 40 | | 40.849 | 0.086 | |
| 50 | | 42.165 | 0.087 | |
| | 1 | 42.839 | 0.087 | 2.674 |
| | | 43.18 | 0.085 | |
| | | 43.599 | 0.084 | |
| 30 | | 44.032 | 0.083 | |
| | 2 | 45.513 | 0.085 | 3.182 |
| 10 | | 47.619 | 0.088 | |
| 0 | 1 | 48.695 | 0.088 | 9.01 |
| 10 | | 49.406 | 0.088 | |
| 20 | | 50.185 | 0.088 | |
| 30 | | 50.942 | 0.087 | |
| 40 | | 51.667 | 0.087 | |
| 50 | | 52.328 | 0.087 | |
| 60 | | 52.908 | 0.086 | |
| 70 | | 53.514 | 0.086 | |
| 80 | | 54.047 | 0.085 | |
| 90 | | 54.546 | 0.084 | |
| 100 | | 55.121 | 0.084 | |
| 110 | | 55.567 | 0.083 | |
| 120 | | 56.054 | 0.083 | |
| 130 | | 56.523 | 0.082 | |
| 0 | 2 | 57.705 | 0.083 | 6.72 |
| 10 | | 58.929 | 0.083 | |
| 20 | | 60.109 | 0.084 | |
| 30 | | 61.135 | 0.084 | |
| | | 62.215 | 0.084 | |
| | | 63.378 | 0.085 | |
| | | 64.178 | 0.085 | |
| 70 | | 64.262 | 0.084 | |
| | 3 | 64.425 | 0.083 | 0.072 |
| | | 64.497 | 0.082 | |

| | Time (sec | Energy (J) | Rate (Hz) | Energy (J) | J/cc |
|---|---|---|---|---|---|
| VCL 1 | 340 | 0.05 | 30.1 | 511.7 | 118.13 |
| VCL 2 | 230 | 0.2 | 30.1 | 1384.6 | 254.91 |
| VCL 3 | 0 | 0.31 | 30.1 | 0 | 0.00 |
| VCL 4 | 0 | 0.45 | 30.1 | 0 | 0.00 |
| | | | Total | 1896.3 | |

- At the Buckskin outcrop PADS drilled down to 64mm
- Starting at VCL 1
- Due to low ROP the system changed the percussion level to VCL 2 at ~12mm
- Due to low WOB, at ~26 mm it reduced the percussion back to VCL 1
- It switches back and forth between VCL 1 and VCL 2 until ~64mm when it ramps up the percussion to VCL 3
    - The depth drilled at VCL 3 was negligible (0.0072mm)
- **The highest percussion level needed was VCL 2**
- The depth drilled at VCL 2 was 30.18mm
- Each millimeter of depth displaces 0.18cc of volume
- The total energy delivered at VCL 2 was 511.7 Joules
- **The percussive energy per unit volume at VCL 2 was 254 J/cc**

# Order of Relative Rock Strengths drilled by PADS



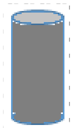


# DARSI Test Flow

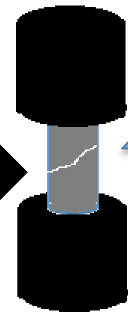
**Manufacture rock test set in Extraterrestrial Materials Laboratory (EMSiL)**

**Strength and Drill Testing**

**Correlation of Drilling Performance Parameters to Rock Strength**



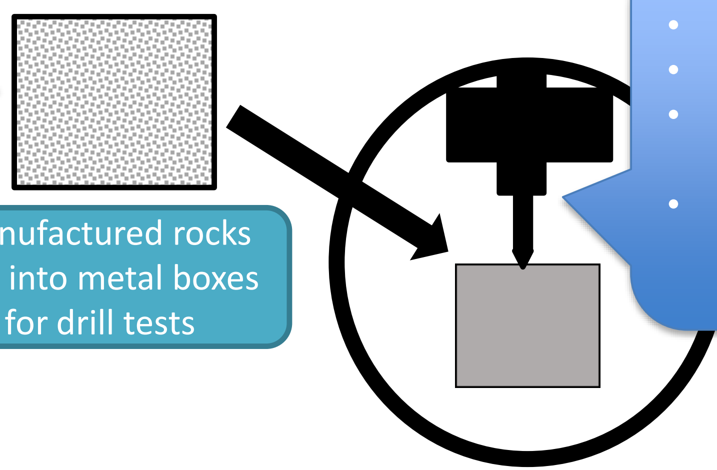
Manufactured rocks cast into cylinders for strength testing



**Strength Testing:**

- Unconfined Compressive Strength
- EMSiL Geotech facility

**Uniaxial Compressive Strength**



Manufactured rocks cast into metal boxes for drill tests

**Drill Testing:**

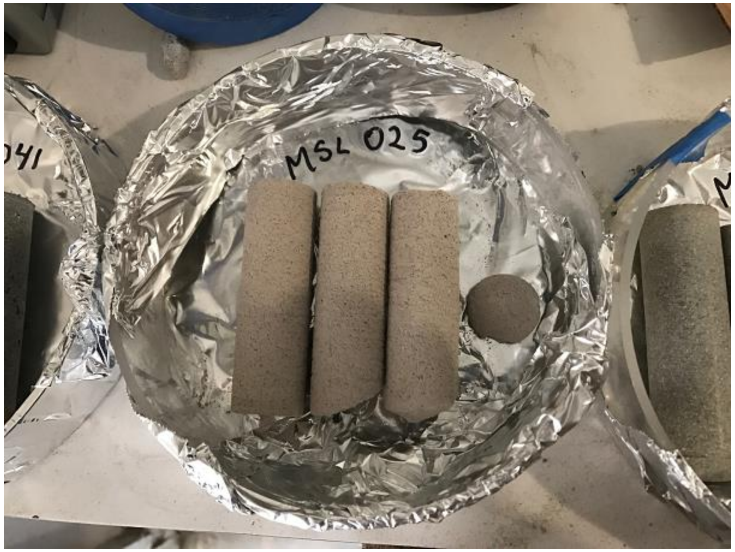
- Depth at VCL
- ROP
- Total Drill On-Time
- RCTB chamber BLG 248

**Drill Parameters**

**Energy per unit volume drilled with a correlation to a known compressive strength**

# DARSI Manufactured Sedimentary Rocks



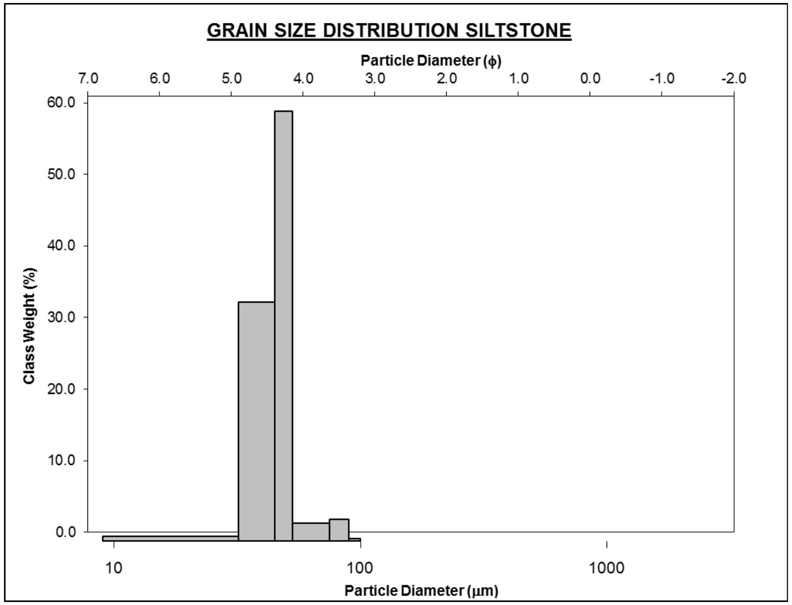


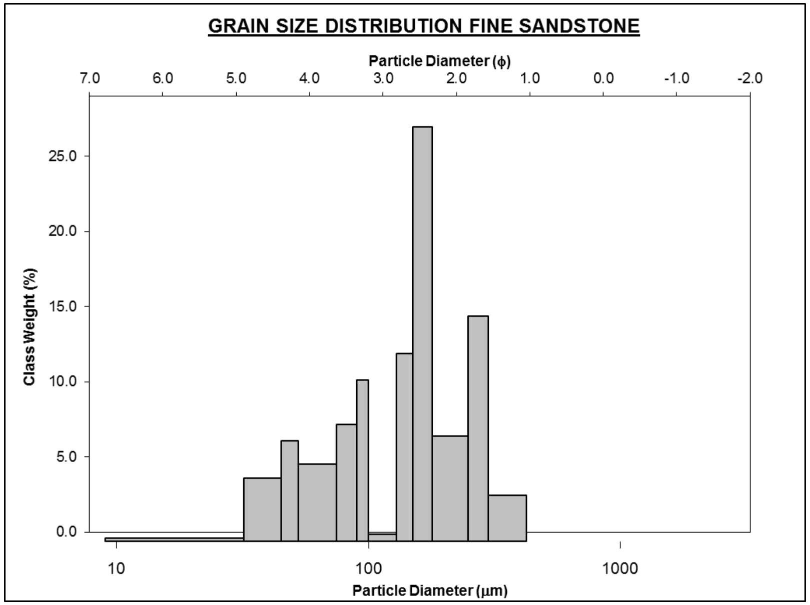

*Images Credit Jet Propulsion Laboratory*

# Particle Size Distributions

- [1] **Murray formation** is lacustrine with fine grains sizes, Phi values **ϕ 2-5**
- **DARSI Siltstone** is a well sorted, coarse siltstone
  - Mean grain size is 44.4μ with a Phi value of **ϕ 4.5**

- [1] **Stimson formation** is aeolian, primarily fine sandstone with Phi values from **ϕ 1-4**
- **DARSI Fine Sandstone** grains size distribution is a bimodal, moderately sorted, silty, fine sandstone
  - Mean grain size is 156μ, with a Phi value of **ϕ 2.6**

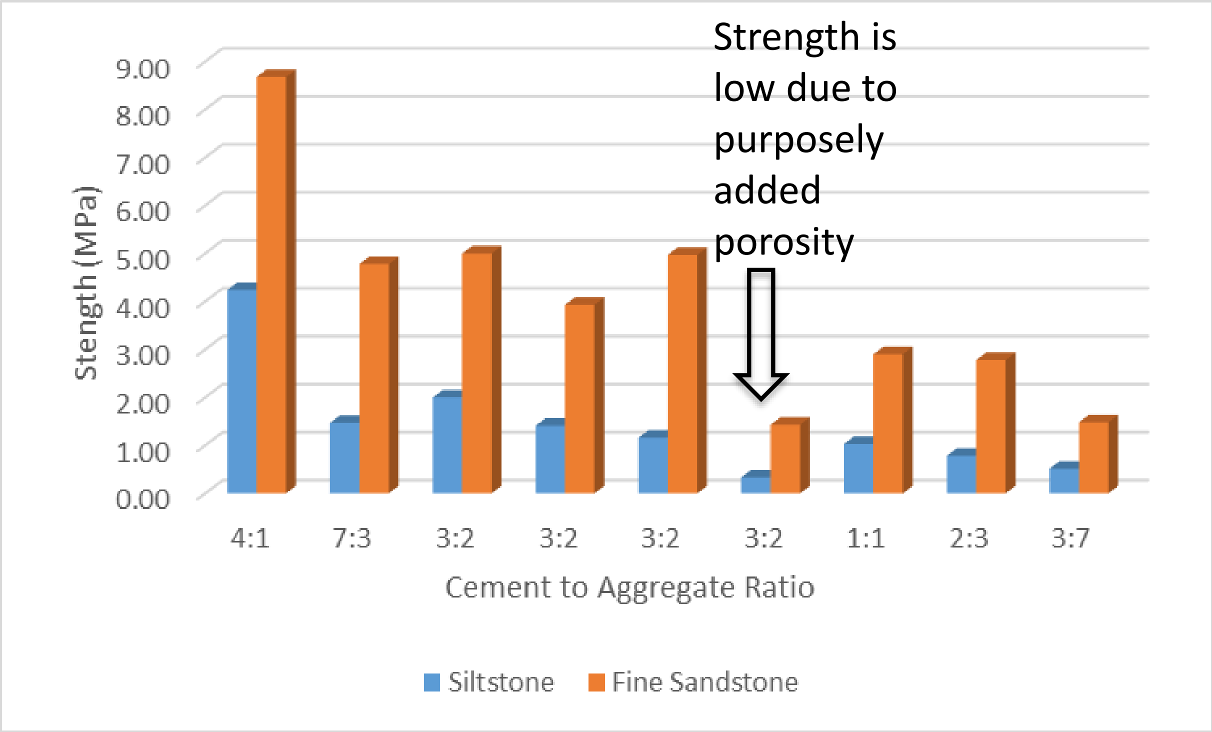



[1] Sacks, L..E.., 2017, GRAIN SCALE ANALYSES OF THE MURRAY AND STIMSON FORMATIONS USING DATA FROM THE MARS SCIENCE LABORATORY MARS HAND LENS IMAGER AND THE CHEMCAM REMOTE MICRO IMAGER , LPSC XLVIII

# Strength Difference Attributed to Particle Size

- DARSI Fine Sandstones are an average of 2.7 MPa (68%) stronger for a given binder to grain ratio than the DARSI Siltstones



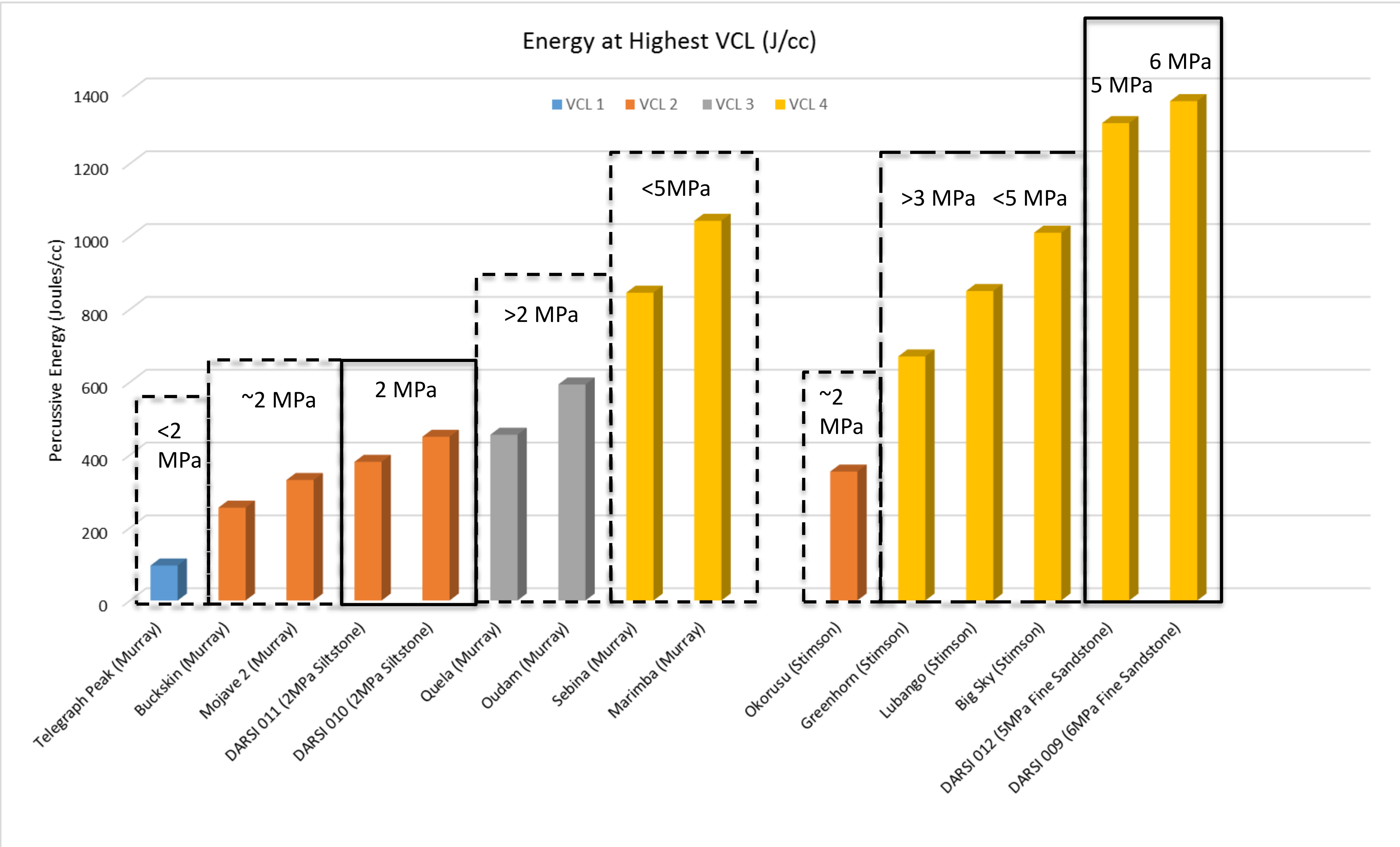

| *Strength Difference Statistics* | |
|---|---|
| Mean | 2.72866667 |
| Standard Error | 0.45405051 |
| Median | 2.52 |
| Standard Deviation | 1.36215152 |
| Sample Variance | 1.85545675 |
| Kurtosis | -1.5635507 |
| Skewness | 0.10486616 |
| Range | 3.585 |
| Minimum | 0.965 |
| Maximum | 4.55 |
| Sum | 24.558 |
| Count | 9 |

# Drilling Environment (fountaining)

- In DARSI rocks the pressure environment can alter results by causing a condition called fountaining
  - After curing, DARSI rocks still contain some water
  - At low pressures unbound water, heated by drilling can flash into vapor
  - Vapor acts as a drilling fluid to remove cuttings
  - Cuttings removal due to fountaining can reduce dampening
  - At Gale Crater the rocks are desiccated
  - No fountaining has been observed
- Here the data represents the testing done at 760Torr
  - It was more important to match the dynamics of the cuttings than the pressure environment

# Assumptions

- Mechanical stresses are distributed through rock in the same manner regardless of the atmospheric pressure
  - Atmospheric pressure has an effect on heat transfer, electrostatics and cuttings transport
  - Unconstrained gasses do not transfer stresses in any significant manner
  - Stress moves through the solid components
- All the rocks we drilled are homogenous
  - We know this is true for the DARSI Rocks
    - We made them!
  - This is likely true for the rocks we drilled on Mars, but there is some uncertainty
    - We can see mineralized layers between laminae, veining and nodules
- Energy where borehole progress is being made, is the only energy that counts
  - Our measurement is the energy per **volume of rock <u>comminuted</u>**
  - Where there is no progress, there is energy expended, but there is no comminution
  - Energy spent going nowhere is not represented in the reported energies of this study


Energy at Highest VCL (J/cc)
VCL 1
VCL 2
VCL 3
VCL 4
Percussive Energy (Joules/cc)
1400
1200
1000
800
600
400
200
0
<2 MPa
~2 MPa
2 MPa
>2 MPa
<5MPa
~2 MPa
>3 MPa
<5 MPa
5 MPa
6 MPa
Telegraph Peak (Murray)
Buckskin (Murray)
Mojave 2 (Murray)
DARSI 011 (2MPa Siltstone)
DARSI 010 (2MPa Siltstone)
Quela (Murray)
Oudam (Murray)
Sebina (Murray)
Marimba (Murray)
Okorusu (Stimson)
Greenhorn (Stimson)
Lubango (Stimson)
Big Sky (Stimson)
DARSI 012 (5MPa Fine Sandstone)
DARSI 009 (6MPa Fine Sandstone)

# Percussion Energy Mapping to Strength

- Recall that where binder to aggregate ratios remain constant, the strength difference between the DARSI Siltstones and the DARSI Fine Sandstones average 68.02%
- After drilling in the testbed we find in the one case where binder to aggregate ratio remains constant, the difference in percussive energy needed to drill a DARSI Fine Sandstone was 68.34% higher than the average energy needed to drill the DARSI Siltstone
  - DARSI 011 was in a siltstone with a 3:2 binder to aggregate ratio
  - DARSI 012 was in a fine-sandstone, also a 3:2 binder to aggregate ratio

| | 3:2 Binder to Agg | | |
|---|---|---|---|
| | DARSI 10 & 011 Siltstone | DARSI 012 Fine S.S. | % Increase from Siltstone to Fine Sandstone |
| Strength (MPa) | 2 (avg) | 5 | 60.00% |
| Percussion Energy (J/cc) | 415 (avg.) | 1311 | 68.34% |
| Average strength difference among 3:2 ratio DARSI Rocks | | | 68.02% |

# MSL Drill Performance Data



| | Mojave 2 Sol 882 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.14 | 29.72 | 290 | 436.45 | 81.59 |
| VCL 2 | 0.10 | 26.92 | 270 | 1625.40 | 335.49 |
| VCL 3 | 0.10 | 0.00 | 0 | 0.00 | |
| VCL 4 | 0.00 | 0.00 | 0 | 0.00 | |
| Total | | 56.64 | | 2061.85 | |

| | Telegraph Peak 908 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.14 | 56.63 | 610 | 918.05 | 90.06 |
| VCL 2 | 0.09 | 0.54 | 0 | 0.00 | |
| VCL 3 | 0.09 | 0.10 | 0 | 0.00 | |
| VCL 4 | 0.00 | 0.00 | 0 | 0.00 | |
| Total | | 57.28 | | 918.05 | |

| | Buckskin Sol 1060 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.09 | 24.07 | 340 | 511.70 | 118.13 |
| VCL 2 | 0.09 | 30.18 | 230 | 1384.60 | 254.91 |
| VCL 3 | 0.08 | 0.00 | 0 | 0.00 | |
| VCL 4 | 0.00 | 0.00 | 0 | 0.00 | |
| Total | | 54.24 | | 1896.30 | |

| | Big Sky Sol 1119 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.05 | 0.98 | 10 | 15.05 | 85.23 |
| VCL 2 | 0.06 | 3.82 | 70 | 421.40 | 613.66 |
| VCL 3 | 0.07 | 8.03 | 100 | 933.10 | 645.48 |
| VCL 4 | 0.07 | 44.08 | 500 | 6772.50 | 853.52 |
| Total | | 56.91 | | 8142.05 | |

| | Greenhorn Sol 1137 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.02 | 0.01 | 0 | 0.00 | |
| VCL 2 | 0.03 | 2.31 | 40 | 240.80 | 579.12 |
| VCL 3 | 0.06 | 18.64 | 190 | 1772.89 | 528.49 |
| VCL 4 | 0.11 | 38.35 | 310 | 4198.95 | 608.22 |
| Total | | 59.32 | | 6212.64 | |

| | Lubango Sol 1320 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.02 | 0.14 | 0 | 0.00 | 0.00 |
| VCL 2 | 0.02 | 1.35 | 20 | 120.40 | 496.58 |
| VCL 3 | 0.07 | 18.37 | 240 | 2239.44 | 677.19 |
| VCL 4 | 0.09 | 38.53 | 350 | 4740.75 | 683.52 |
| Total | | 58.39 | | 7100.59 | |

| | Okoruso Sol 1332 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.08 | 36.53 | 420 | 632.10 | 96.14 |
| VCL 2 | 0.09 | 21.82 | 180 | 1083.60 | 275.94 |
| VCL 3 | 0.00 | 0.01 | 0 | 0.00 | |
| VCL 4 | 0.00 | 0.00 | 0 | 0.00 | |
| Total | | 58.35 | | 1715.70 | |

| | Oudam Sol 1361 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.03 | 0.68 | 10 | 15.05 | 122.96 |
| VCL 2 | 0.06 | 10.07 | 120 | 722.40 | 398.62 |
| VCL 3 | 0.09 | 47.09 | 540 | 5038.74 | 594.41 |
| VCL 4 | 0.01 | 0.03 | 0 | 0.00 | |
| Total | | 57.88 | | 5776.19 | |

| | Marimba Sol 1422 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL1 | 0.08 | 30.37 | 330 | 496.65 | 90.85 |
| VCL2 | 0.09 | 3.81 | 20 | 120.40 | 175.42 |
| VCL3 | 0.05 | 3.11 | 70 | 653.17 | 1166.79 |
| VCL4 | 0.07 | 21.64 | 300 | 4063.50 | 1043.45 |
| Total | | 58.93 | | 5333.72 | |

| | Quela Sol 1464 | | | | |
|---|---|---|---|---|---|
| | Avg. ROP (mm/sec) | Depth (mm) | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.12 | 18.61 | 150 | 225.75 | 67.39 |
| VCL 2 | 0.06 | 14.25 | 220 | 1324.40 | 516.41 |
| VCL 3 | 0.11 | 23.12 | 180 | 1679.58 | 403.57 |
| VCL 4 | 0.00 | 0.00 | 0 | 0.00 | |
| Total | | 55.98 | | 3229.73 | |

| | Sebina Sol 1495 | | | | |
|---|---|---|---|---|---|
| | Average ROP | Total Depth | Time (sec) | Energy (J) | J/cc |
| VCL 1 | 0.12 | 22.71 | 190 | 285.95 | 69.96 |
| VCL 2 | 0.11 | 1.19 | 10 | 60.20 | 280.81 |
| VCL 3 | 0.09 | 21.27 | 290 | 2705.99 | 706.82 |
| VCL 4 | 0.09 | 13.63 | 150 | 2031.75 | 827.89 |
| Total | | 58.80 | | 5083.89 | |

# Conclusions

- Rock Structure must be considered
- Percussion energy maps well to strength
- Murray mudstones and the Stimson fine-sandstones are weak
  - The Murray formation rocks range from less than 2 MPa to 5 MPa
- Stimson fine sandstones have been more often stronger than the Murray at 3 MPa to 5 MPa

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